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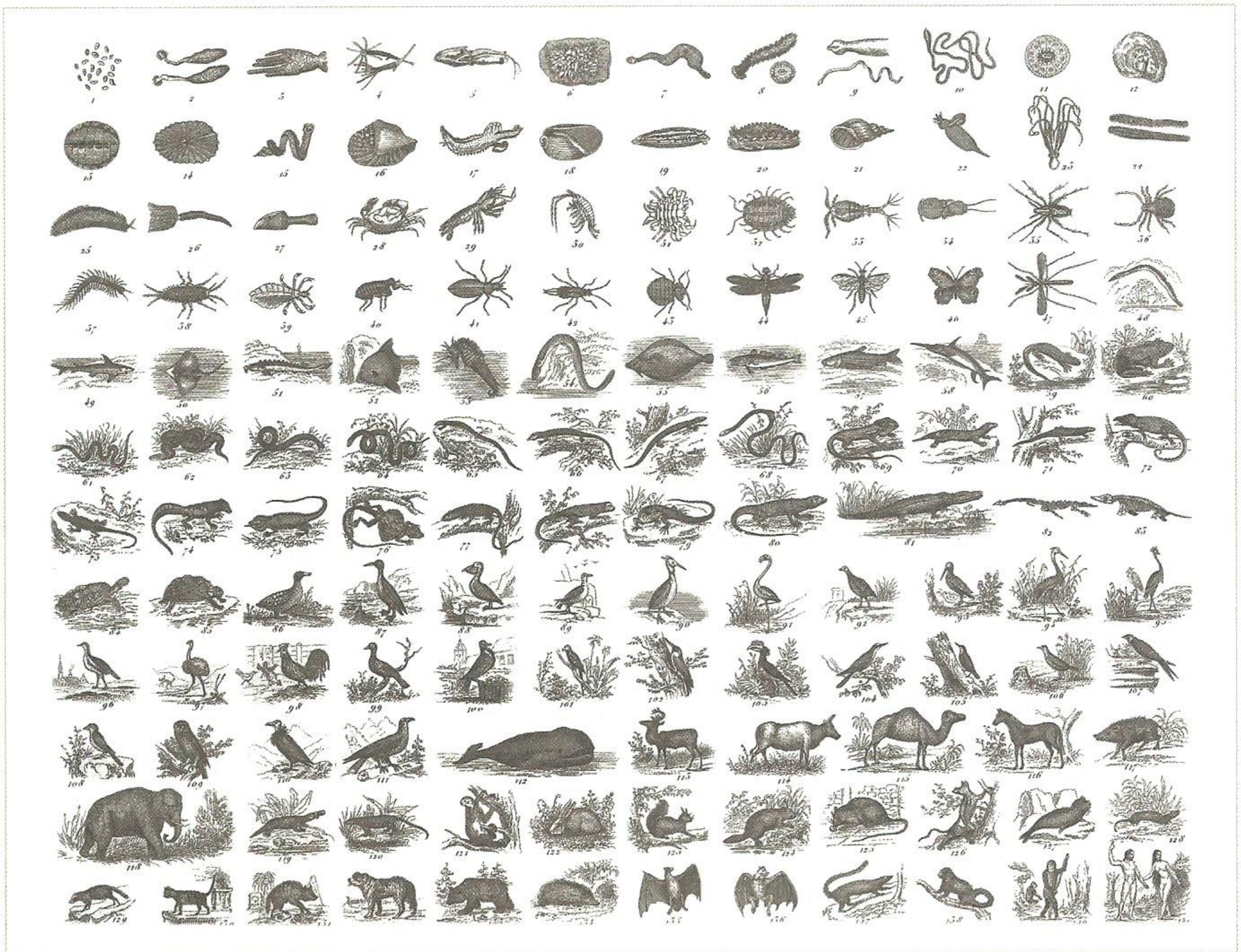
NATURAL HISTORY. Originally, natural history was the study of the natural world in all its observable diversity, embracing animals, plants, minerals, and aspects of what now fall under archaeology, anthropology, geography, meteorology, and geology. The objects of study were not always of living origin, as in the observation of weather patterns; nor were they always of natural origin, as in the collection of ancient coins or man-made artifacts such as prehistoric pottery. The term "natural history" perhaps ought to be regarded as a designating technique rather than as a subject area. To conduct a natural historical study was to collect, describe, classify, and from the seventeenth century onward, to perform minor experimental investigations into observable phenomena. At heart, it was descriptive, depending on a large variety of examples collected and arranged for edification, inclusive rather than exclusive, and rarely reductive in the form otherwise developed by Western natural philosophers. In this sense, natural history takes its origin in the encyclopedic endeavors of authors such as Pliny the Elder. Pliny's *Natural History* in thirty-seven books dealt with cosmology, geography, anthropology, zoology, botany, medicine, chemical recipes, mineralogy, magic, and human industry and art, a miscellany of information for the most part comprising extracts from other authors.

The Swedish botanist Carl von Linné (1707–1778) in Lapp clothes. During his expedition to Lapland in 1732, he covered over 7300 km.

The ancient and medieval scholar described living things by particular properties, uses, or wonders so that others might use or wonder at them. Moral and didactic themes were overwhelmingly important. Manuscripts and early printed books included references to fables, astrological correspondences, religious symbolism, and what are now considered imaginary beasts. The illustrations that accompanied these descriptions were often partly imaginary and stylized, especially in illuminated manuscripts of the Romanesque tradition. Alexander Neckham discussed the virtues of herbs alongside the theological cause for spots on the moon and insect venoms. Studies of nature typically took the form of catalogs and encyclopedias, like that of Bartolomaeus Anglicus's *On the Properties of Things,* which became one of the earliest printed works. Bartolomaeus and others displayed great erudition in their sources and shrewd observation by adding their own opinions and commentaries to older sources. They covered herring fisheries, agriculture, mining techniques, falconry, and such like, and gave the first accounts of exotic animals, plants, and medicines brought back from early voyages of exploration. A form of emblematic natural history emerged, based on a complex system of associations and similitudes, mostly astrological and moral, that was also learned and eclectic, full of compilations from earlier texts and oral knowledge.

Highly naturalistic representations of plants and animals were displayed throughout Europe in church decorations and illuminated manuscripts. Manuscript illuminators learned three-dimensional realism from the artists of Italy and Flanders. Both the naturalistic and Romanesque traditions continued without a break into the early printed herbals. The level of popular knowledge of natural history in the medieval and Renaissance periods can be inferred from these artifacts.

After 1650, naturalists abandoned emblematic meanings in order to focus more obviously on description and anatomical investigation. They studied and collected natural objects both for themselves and as part of a broader interest in curiosities. Books such as Robert Plot's *Natural History of Oxfordshire* (1677) discussed all sorts of local features, including country houses of the region. Books based on particular geographical regions became an established genre associated particularly with the recreations of gentlefolk, the "virtuosi" or gentleman-scholars of the period. Collecting rarities, performing experiments, and traveling and discussing their finds in clubs and societies were accepted activities in European aristocratic culture. In describing curiosities, scholars consciously adopt-



A late rendition of the animal world according to the French zoologist and paleontologist Georges Cuvier (1769–1832). The taxonomy runs from a cellular organism to man. From Johann Georg Heck, *Bild-Atlas* (1860).

ed a new style of descriptive language based on observation. Frequently, they reported measurements.

During the late seventeenth and eighteenth centuries, observations of the weather formed an important part of local natural history. Weather-books and garden calendars, in which the owner recorded the weather regularly, were introduced, emerging from the long-standing tradition of almanacs. Small museums and displays, often including antiquities, multiplied, and private menageries became popular among the wealthy. The older universities established physic gardens in which the whole of God's creation might be collected together and museums or cabinets in which curiosities from around the world could be shown.

Beginning in 1620, the Society of Apothecaries, one of the old-established livery companies of London, organized herborizing expeditions; similar expeditions followed in Edinburgh from 1670. These activities were seminal in establishing the field tradition that characterized European natural history thereafter. Since many enthusiasts for natural history were also physicians, collections often ranged widely over the disciplines, and frequently became the subject of inquiry or experiment. Putting together a "natural history of mankind" was a favorite endeavor that variously included reports of new races of humanity in exotic lands, folklore or other accounts of human societies, interesting artifacts, musings on the geographical distribution of mankind, and comparative anatomy. Natural history came to mean an account of nature based on information acquired by observation and inquiry (including textual and verbal inquiry)—a point of view generally endorsed by forward-looking physicians. Doctors figured prominently among the early Fellows of the Royal Society, and medical societies and colleges formed some of the finest natural history collections still extant. Other enthusiasts typically formed a small club or local society to facilitate expeditions and the exchange of specimens and information. Generally these groups embraced a wide range of subject matter, and were among the first nonprofessional associations in many provincial towns in Europe. They played a major part in developing the strongly localized basis of British natural history.

During the eighteenth century, the subject's diffuse qualities gave natural history a low position in the hierarchy of the sciences. Countless descriptive papers appeared in the *Philosophical Transactions* of the Royal Society, devoid of the analytical spirit typifying French or Italian scholarly endeavor. The intellectual futility of these articles was lampooned by Jonathan Swift in *Gulliver's Travels,* and Jean Le Rond d'Alembert deprecated mere description in his preliminary discourse to the *Encylopédie* (1751).

Outside the learned world, natural history was understood to relate mostly to animals, plants, meteorology, and geology. Collecting objects and making observations became the central defining feature, encouraged by the growth of convivial clubs and outings. Techniques for recording data and collecting specimens consolidated. Naming and arranging specimens preoccupied many, both inside and outside museums. Books and catalogs were produced, and specimens sold or exchanged in a rapidly developing market economy.

In Britain, Gilbert White, the chronicler of the *Natural History of Selborne* (1789), became the exemplar of these localized pursuits. An Anglican clergyman, White regarded natural history as an appropriate way to appreciate the wonder and perfect design of God's creation. The Abbé Pluche in France wrote in much the same manner on the *Spectacle of Nature, wherein the wonderful works of Providence in the animal, vegetable and mineral creation are laid open* (1754). Natural history became closely associated with the natural theological tradition. Not all exponents made obeisance to religion, however. Thomas Pennant barely referred to the Creator in his *British Zoology* (1766), noted for its naturalistic illustrations and keen observation of bird behavior and habitat.

Fashionable interest during the eighteenth century perceived natural history as suitable for cultivation by women and gentlefolk, both literally in the development of lavish gardens and landscapes, greenhouses, menageries, and the breeding of rare livestock, and more passively in providing a responsive market for fine illustrated books, elementary teaching manuals, artworks, and newly fashionable decorated wallpapers and fabrics. Few other sciences have been taken up by consumers in such an obvious manner.

To be sure, Carl Linnaeus's simplification of classification and nomenclature enabled people who worked with animals and plants to codify their observations. Travelers and collectors could quickly assign unidentified plant specimens into a class or family. Linnaeus trained and sent plant collectors all over the increasingly accessible globe—Japan, South Africa, the Carolinas, Asia, central Spain, and so on. These men, whom he called "apostles," and others using his system, sent numerous collections back to Europe throughout the eighteenth century; Linnaeus consciously served as the hub of a botanical exploring network fanning out from his base at the medical school of Uppsala University. His classification scheme also helped botanical knowledge to move out of the restricted domain of universities, museums, and physic gardens into a broader constituency. Many eighteenth-century figures, including gentlefolk, women, and working men, are all known to have first encountered botany through popularizations of Linnaeus's system. His "sexual system" provided the basis for much cultural satire and parody, ranging from sexual innuendo about plants acting as humans to a scurrilous anti-Catholic classification of monks.

A growing interest in landscape gardening and the cult of the picturesque also stimulated interest in natural history. Plants and animals played a significant role in the life of the landed elite, who often possessed illustrated books and synopses of classification schemes in their libraries. The landed gentry patronized specimen collectors and landscape gardeners. Hothouses and stove-plants became an increasing possibility for the wealthy.

Natural history's greatest impact, however, came through geographical expeditions. These introduced a large number of new species to the West, initiating a rage for choice specimens and providing the foundations of national herbaria and museum collections. Many of these exotics came from government voyages of exploration to the Pacific, Australia, the Cape (of Good Hope), and the Americas. Living exotics could be seen at Kew Gardens (royal property until 1841), Chatsworth, or Syon Park near Chiswick, and the great European gardens such as the Jardin des Plantes in Paris. Enterprising private societies such as the Royal Horticultural Society (founded in 1804) and the Société d'acclimatisation in Paris sponsored collecting trips abroad and ran public gardens and competitions for their members. Animals were displayed in private and commercial menageries as well as in museums. The arrival of living examples of Nubian giraffes in Paris or London for these collections aroused national interest.

European prosperity overseas increasingly depended on the development of the plantation system in which staple crops such as tea or sugar-cane were relocated for colonial purposes. Local observers—frequently European expatriates—helped collectors back home. Naval officers, commercial entrepreneurs, and overseas residents gradually opened up the knowledge base of many different regions. In Britain, the East India Company took the lead in establishing botanical gardens in Saharanpore and Calcutta, and Kew Gardens, under Sir Joseph Banks, became a hub of proto-imperial science. The rich collections in Paris and the Netherlands were already the envy of Europe.

During the eighteenth and nineteenth centuries, natural history underwent a profound intellectual transformation. Interest in producing classification schemes was edged out, though never entirely replaced, by investigations into the inward functions of organisms and the history of living beings over time. Natural history itself slowly separated into subdisciplines such as paleontology, each with their own methods, agendas, and subject-matter. When the Museum d'Histoire Naturelle was reformed in post-Revolutionary France, the academic work undertaken within its domain was especially significant. Georges Cuvier explored the fossil world, and restructured classification schemes on the basis of four irreducible "types." His analysis of the elephant genus codified the concept of extinction.

Throughout Europe and America, a Christianized version of Cuvier's explanation of earth history became generally accepted. This invoked a series of creations of living communities of animals and plants periodically subject to catastrophic extinctions. Each successive creation advanced in character beyond its predecessor. The modern epoch, which included mankind, dated only from the Biblical flood, which coincided with the watery, icy period that naturalists recognized in the geologically recent past. This cold period divided the ancient history of the earth and the reign of mankind—and, if necessary, more or less matched the Biblical story. Cuvier's work was extensively popularized and had an impact on general natural history as well as in elite academic fields. The transformist schemes of his contemporary, Jean Baptiste de Lamarck, were less acceptable to the elite, but quickly spread in radically politicized form among progressive medical men in Europe.

Nineteenth-century natural history for the most part served Christianity. The geographical expansion of Europe's political and trading dominions, and the rapid economic development of North America, included a generalized Christianizing and educative mission in which natural history was frequently a significant element. Colonialists thought it important that natural history specimens, once collected overseas, be brought back to developed nations where they would be identified, itemized, and displayed as physical tokens of Western knowledge and, in many cases, colonial possession. In this fashion, butterflies from Surinam (say) served as effective devices to display scientific imperialism. Once named, said the British entomologist William Kirby, a thing becomes a possession. An extensive network of naval officers, surgeons, travelers, and local residents, distributed over the globe, contributed to a supply system—a flow of information mostly from the peripheries to the centers of knowledge in Europe's and America's capital cities. This flow of information to an administrative center, and the human networks on which it depended, mimicked the bureaucracies and administrative structures springing up in colonial countries.

Nineteenth-century natural history, like astronomy, lent itself to an imperialist structure. To a large degree, Charles Darwin's work was built on just such a structure. He considered himself a naturalist of the widest possible remit, interesting himself in turn in geology, plant life, animal breeding, coral reefs, insects, barnacles, and earthworms, and generally wrote in the pastoral mode created by Gilbert White. His work was nevertheless distinguished from the milieu in which he felt most relaxed by the strongly reductionist laws that he proposed to account for species change in nature. Since his day, natural historians have often justified their work and taken comfort from the fact that Darwin was at heart a naturalist and observer like themselves.

After reaching a peak in the middle years of the nineteenth century, the social and intellectual status of natural history underwent a relative decline with the rise of laboratory biology. During the same period, the popularization of science developed as a large-scale enterprise, disseminating scientific information of all kinds to the public at large. Natural history remained a favorite topic of books and magazines, lectures, exhibitions, and museums. This commercial success distinguished it from most of the other sciences. Lively, picturesque descriptions became the accepted norm, often featuring accounts of animal behavior.

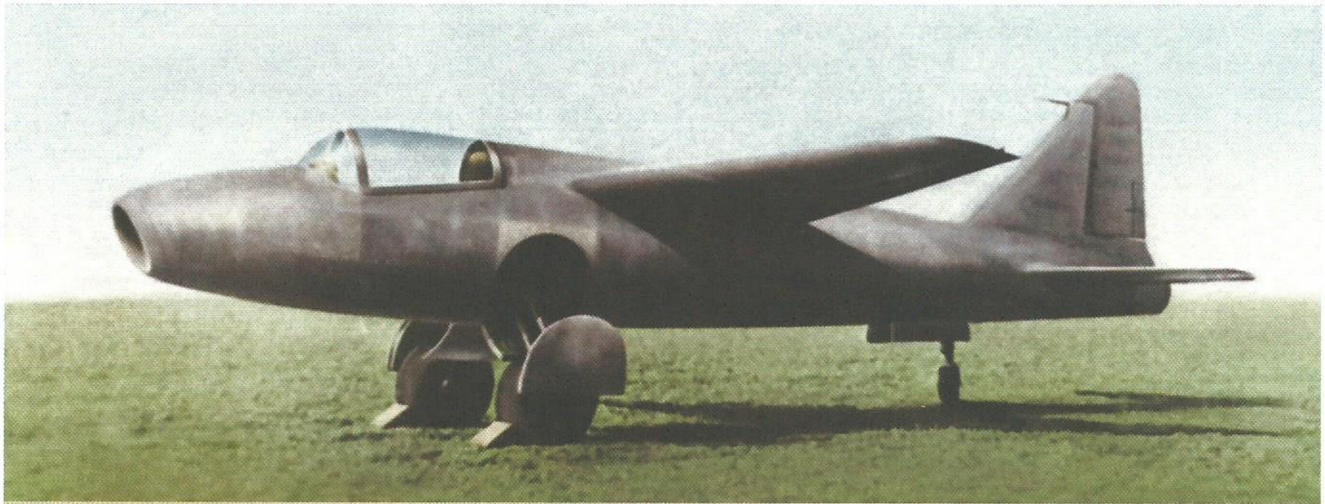
Women formed an important category of authors, readers, and gardeners. They wrote books, attended public lectures, and encouraged the discipline in a domestic setting. An exceptionally accessible subject at a time when science was become increasingly abstract and mathematical, natural history seemed to belong to everybody. Anyone could advance it by observing or collecting. Amateur naturalists and volunteers in the field collaborated with newly professional university experts, although relationships could be tense. An indication of the growing distance between professionals and amateurs is the development of ecology. It did not emerge from field observations or inherit the characteristics of nineteenth-century natural history, even though one of its founders, Charles Elton, wrote that ecology was in essence "scientific natural history." In fact, it emerged in opposition to the natural history tradition in a movement in which professionals rejected the natural historical as amateurish and disorganized, not subject to rigorous controls or experiment.

This aura of accessibility continued to be the defining feature of natural history through the twentieth century, aided immeasurably by the development of cinema, photography, and television. Environmentalism and "green" policies have furthered the public appeal of the subject.

Janet Browne

NAZI SCIENCE refers in a general sense to all science, its practitioners, and its policy during the Third Reich (1933–1945), and more specifically only to those sciences directly tainted ideologically in content or in application by National Socialist policy. To the occupying powers, all scientists who remained in the Third Reich were "Nazi scientists" for purposes of denazification. For decades after World War II, the historical examination of science under National Socialism was taboo. Since the publication in 1977 of Alan Beyerchen's groundbreaking study of Nazi physics, the extent of Nazi influence has been revealed and the difference between "science in the Third Reich" and "Nazi science" has diminished. Under Hitler, nearly all areas of science, technology, and medicine, and indeed of scholarship in general, were influenced by the Nazi regime in content, practice, policy, or administration. Historians have tried to understand how and why sciences not obviously relevant to National Socialism still became more or less Nazified in content or approach. Nazi science is thus one of the most important historical examples of the relationship between science and ideology.

The most obvious of the Nazi sciences was Aryan science. The purging of Jews from state positions under the Nuremberg Laws of 1933, and the accompanying elimination of "Jewish theories," such as relativity, from textbooks, led attempts to create ethnically pure varieties of science that embodied National Socialist values. Aryan science included the application of rationality and efficiency to pressing state problems, especially the "Jewish Question" and the infamous Final Solution. It also became manifest in fields as diverse as physics, chemistry, mathematics, and psychology. Once politically objectionable individuals had left Germany, the state or party orchestrated the decline of Aryanized disciplinary science—except for certain forms of the biomedi-



The He-178, the first jet plane, designed by Heinkel in the late 1930s, made its first major flight on August 27, 1939. Its competitor, Messerschmidt's Me-262, was the first mass-produced jet fighter.

cal, engineering, and social sciences useful in attaining Nazi social and political objectives.

Although Nazi racial policy had links both to Social Darwinism in Imperial Germany (1871–1914) and the racial hygiene and eugenics movements in the Weimar Republic (1919–1932), the execution and administration of those policies were distinctive and tragic occupations of the Third Reich. Already, Weimar Germany used euthanasia in mental institutions and co-opted biology instruction, even at introductory levels, to teach racial purity, civic-mindedness, health, and hygiene. Although some biologists remained unaffected by the Third Reich, biology and the biomedical sciences were mobilized in war-related projects in research institutes or concentration camps on twins, eye color, air pressure, and reproduction. Genocide could only be accomplished with the chemical weapons created during World War I and further developed and deployed in medical settings outside the military in the 1920s. Part of Nazi racial policy involved the resettlement of Germans in eastern Europe. Area studies and spatial planning policy, using a multi-disciplinary approach based on geography, provided the practical details needed to implement the plan. This *Ostforschung,* or research on the east, presumed that the Polish, Jewish, Russian, and Ukrainian populations of eastern Europe would be expelled or murdered. The loss of the war thwarted the project to resettle the east, but the principles of urban and spatial planning developed for it remained useful. Elements of it figured in the reconstruction of West Germany, especially in handling the influx of German citizens forced to leave the eastern sections of the former Reich.

In defiance of the Versailles treaty, the Nazi regime supported military science and technology beginning with the introduction of armaments research in engineering courses at the technical universities in the early 1930s. In 1936–1937, the Reich openly supported military weapons projects; its devastating loss in the *Blitzkrieg* (lightning war) of 1941–1942 intensified its weapons research. In principle, Hitler himself had to approve all major military research and development projects, but bureaucratic conflicts led to inconsistent oversight of even the most strategic of them, including aeronautics, the uranium bomb, and rocketry.

Aeronautical research, based at Ludwig Prandtl's Göttingen institute, effectively circumvented the restrictions of the Versailles treaty, but was stymied occasionally by covert acts of resistance. Nevertheless, aeronautics became not only a Nazi strength, but later a West German one as well.

The uranium project under Werner Heisenberg, one of the most enigmatic projects of the Third Reich, failed to build a bomb; Heisenberg nonetheless went on to become the most important public spokesman for science in democratic West Germany and a major figure in promoting West German nuclear power plants. The guided missile and rocketry project under Wernher von Braun was the most outstanding technological success of the Third Reich. Under the Army's administration at first, the rocketry project expanded when the Air Force took over in 1935, and then again at Peenemünde and eventually in an abandoned mine in the Harz Mountains near Nordhausen, where concentration camp prisoners from Buchenwald supplied the labor for the protection of the vengeance weapon, the V-2, which Hitler believed would win the war. Both the Americans and the Soviets captured nearly all of Hitler's rocket scientists. During the Cold War, the Germanies had hardly any space program, while the superpowers explored space and escalated international tensions with the help of former leaders of Nazi missile projects.

That the Third Reich was not more successful in science and technology has to do in large part with the fractious nature of its internal politics. A state that appeared to be run rationally was weakened by competition among power groups that precluded success in major projects. Where broad definitions and goals guided policy and administration—in matters concerning military technologies, race, gender, *Lebensraum* (living space) in *Mitteleuropa,* and *Gleichschaltung* (social coordination, or alignment with the regime)—science and technology were for the most part effectively co-opted. The most successful of the Nazi policies in science, racial cleansing and genocide, were also the most tragic. The alliance of science, technology, and medicine with the National Socialist technocracy led to a reorganization of scientific administration that survived the Reich and helped to create the big science methods of management found in both Germanies after 1945. These administrative strengths contributed significantly to the rebuilding of the scientific community after 1945, and eventually enabled both Germanies to compete scientifically with the superpowers during the Cold War. In both its short-term and long-term successes, however, Nazi science cannot evade moral judgement.

KATHRYN OLESKO

NEWTONIANISM. Isaac Newton joined terrestrial and celestial mechanics together in 1687 with the publication of his *Philosophiae naturalis principia mathematica,* transforming the two kinds of physics into a single system oriented around the inverse-square law of gravitational attraction. Twenty years after this feat of mathematical synthesis, Newton contributed to framing experimental physics in his *Opticks; or, A Treatise of the Reflections, Refractions, Inflections and Colours of Light,* first published in 1704 and going through four editions by 1730. The *Opticks* laid out an experimentally derived geometry of light-rays, including the use of prisms to analyze white light into the colors of the spectrum and then resynthesize them into white light. The *Opticks* also included a final section of "queries" containing all the unfinished business of Newton's career. By means of this laundry list, Newton set the agenda for his eighteenth-century followers. Most importantly, he proposed that weightless ethers were the medium and material cause of forces and phenomena including light, heat, electricity, magnetism, gravitational attraction, and animal sensation.

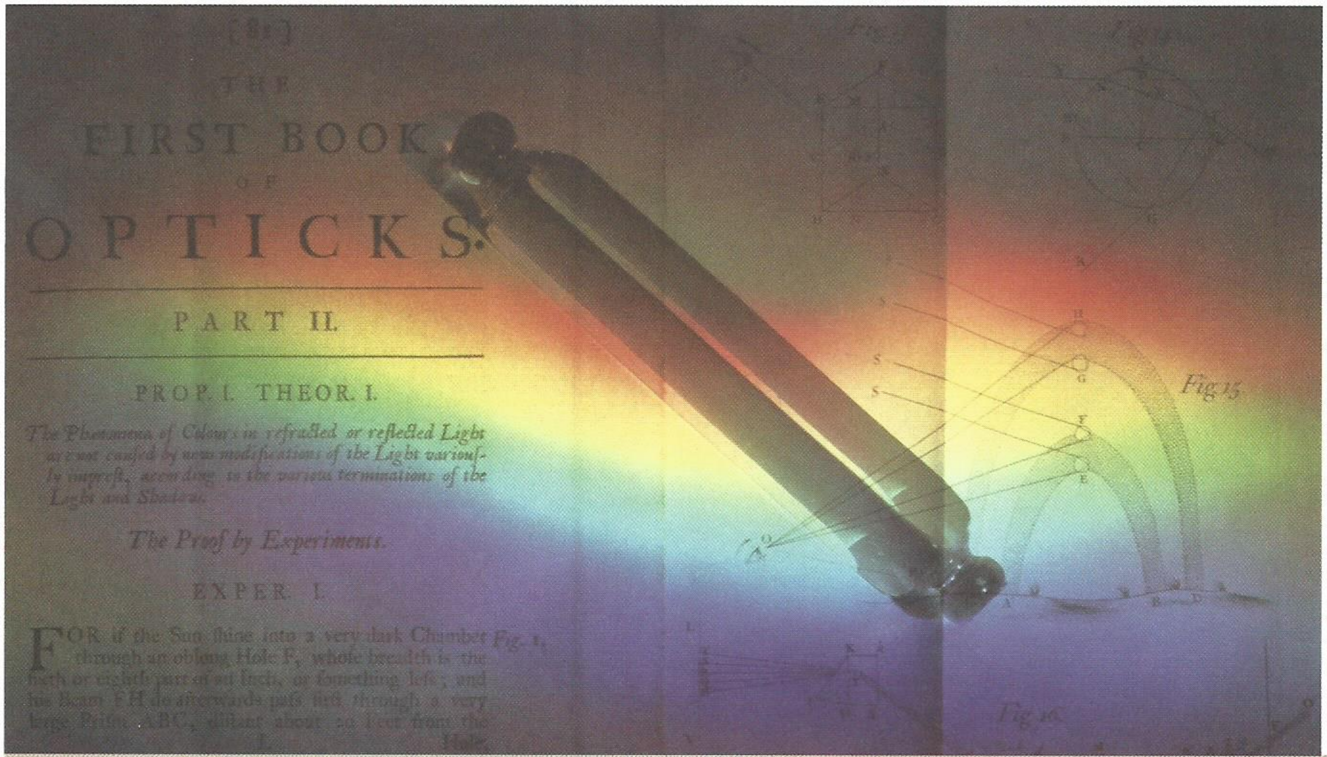
Over the past three centuries, "Newtonianism" has meant several things. On the model of the *Principia,* it has meant a mathematical, synthetic approach to physics, and more specifically, the confirmation and promulgation of inverse-square laws of force. Important examples are John Mitchell's demonstration of an inverse-square law for magnetic force (1750) and Charles Augustin Coulomb's announcement of an inverse-square law governing electrical attraction and repulsion (1785–1789). Eighteenth- and nineteenth-century Newtonians also developed the field of astronomy by testing Newton's law of gravitational attraction against new observations and resolving apparent conflicts. Alexis-Claude Clairaut's explanation of the motion of the lunar apogee (1749) and his accurate prediction of the return of Halley's comet in 1759 confirmed and vindicated Newtonian astronomy. These efforts gave rise to an increasingly complex picture of the mutual gravitational influences of celestial bodies. The culmination of eighteenth- and early nineteenth-century Newtonian astronomy was Pierre-Simon Laplace's *Traité de mécanique céleste* (1798–1827), in which Laplace used Newton's law of gravitation to develop a complete theory of the solar system, taking into account complexities such as the perturbations in the orbits of the planets and the satellites caused by their mutual attraction.

On the model of the *Opticks,* meanwhile, Newtonianism has meant an inductive, experimental approach to physics. Users of this meaning of the word cite Newton's promise, in the preface to the *Principia,* to "feign no hypotheses." An example of a Newtonian in this sense is Benjamin Franklin, who presented his electrical science as one founded in experimental tinkering rather than theory. His followers and historians have likened him, on that basis, to the Newton of the *Opticks,* the empirical essayer and querist. The empiricist meaning of Newtonianism has also referred, more specifically, to the use of analysis and synthesis experiments, for which Newton's investigations of white light served as the paradigm. The leading eighteenth-century example of experimental Newtonianism in this sense is Antoine-Laurent Lavoisier's analysis of water into hydrogen and oxygen and his resynthesis of these elements into water (1785).

The *Opticks* gave rise, finally, to a third meaning of Newtonianism, to describe the eighteenth-and nineteenth-century research program of so-called imponderable fluids that grew from Newton's hypothesis regarding force-bearing ethers. The hypothesis that an imponderable fluid medium carried each force informed theories of electricity, magnetism, heat, and light well into the nineteenth century. An eighteenth-century example of a fluid theory was Franklin's account of electricity, according to which a weightless electrical fluid, whose particles were mutually repulsive, permeated common matter, balancing the mutual attraction of its particles. Electrical effects accordingly resulted from the depletion (negative charge) or overabundance (positive charge) of the electrical fluid in a body. Another important eighteenth-century example was Joseph Black's understanding of heat. Black noticed that it took a great deal of heat simply to melt ice, without changing its temperature. He gave the name "latent heat" to the thermal fluid that seemed to disappear during phase changes, and he distinguished the quantity of this fluid in a heated object from its density, defining temperature as density of heat. An object's temperature depended, Black reasoned, upon its substance's capacity to contain the thermal fluid. These early notions of negative and positive electricity, of latent heat and of heat capacities, or specific heats, were thus informed by the Newtonian paradigm of imponderable fluids.

In addition to the work set forth in the *Principia* and the *Opticks,* another factor was crucial in shaping the meaning of Newtonianism, particularly during the eighteenth century: the contrast—partly genuine, but also overdrawn by Newton and his followers—between Newton's approach to physics and that of the French mathematician and natural philosopher René Descartes, to whose example Newton owed the beginnings of many of his ideas. Descartes notoriously allowed his rationalism and his commitment to rigorously mechanical explanations of natural phenomena to get the better of his physics. Based upon the principle that there could be no intelligible difference between matter and space, and on the conviction that physical events must have mechanical causes in the form of pushes between bits of matter, Descartes derived a picture of the universe as a great plenum in which all things were constrained to move in vortices. Newton's followers called Cartesian physics dogmatic, misguided, and arrogant in its claims to completeness. They pointed to Newton's abstention, in the *Principia,* from assigning a mechanical cause for gravitational attraction as the epitome of empiricist open-mindedness and humility. In celebration of what they took to be his epistemological modesty, Newtonians often referred to Newton's remark that he was merely collecting pretty pebbles beside the ocean of truth.

Leaving a gap at the heart of his system of mechanical causation, Newton allowed his disciples to fill in the metaphys-



Photograph illustrating Isaac Newton's (1642–1727) ideas on the origin of the spectrum published in *Opticks* of 1704 ics of their choosing. He himself wrote, in the queries to the *Opticks,* that natural phenomena arose not from mechanical causes, but from the will of a divine intelligence. This appeal to a final cause lying beyond the efficient ones pleased Enlightenment eulogists of Newton's mechanical system, who showed a remarkable tendency to cite its breaches. An example is David Hume's satisfaction that although Newton "seemed to draw off the veil from some of the mysteries of nature," he also demonstrated "the imperfections of the 'mechanical philosophy,'" restoring Nature's secrets "to that obscurity in which they ever did and ever will remain" (*The History of England* [1754–1762]). Voltaire, in his *Lettres philosophiques* (1734), popularized for a French audience the contrast between Newton's heroic acceptance, and Descartes's dogmatic refusal, of obscurity.

We now have four meanings of Newtonianism: a mathematical, synthetic approach to natural philosophy (particularly one founded in inverse-square laws of force); an inductive, experimental approach to natural philosophy (particularly one founded in analysis and synthesis experiments); the attribution of forces to weightless, force-bearing ethers or "imponderable fluids"; and the appeal to final causes, manifestations of the will of a divine intelligence, as the ultimate cause of natural phenomena, in contrast with Descartes's and his followers' strict adherence, in their natural philosophy, to mechanical causes.

The promulgation of Newtonianism coincided with an increasing interest in natural knowledge among the literate public. Some of the first people to teach courses of experimental physics were Newton's propagandists: Francis Hauksbee and John Theophilus Desaguliers, demonstrators at the Royal Society of London, and Willem Jacob 'sGravesande, professor of mathematics at the University of Leiden, who was inspired by a meeting with Newton during a visit to London. These lecturers professed to translate Newton's physics from the language of mathematics into the language of experience, using demonstration experiments to make complicated ideas accessible to polite audiences. Popular written expositions of Newton's physics, including Desaguliers's and 'sGravesande's published lectures, emerged during the first third of the eighteenth century. Turning Newton's natural philosophy into a source of philosophical amusement, lecturers and authors established in the minds of their public a particular model of natural knowledge: quantitative and synthetic but also rigorously experimental; materialist and mechanist but also resting upon an underlying assumption that the ultimate causes in nature were final rather than efficient, reasons rather than mechanisms. The same model of knowledge took root in universities, academies, and technical and professional schools during the eighteenth century, beginning with the Royal Society, Cambridge University, and the University of Leiden, and spreading after about 1730 to France, Italy, Russia, and Sweden, where it mixed with continental traditions informed by the work of Descartes, Gottfried Leibniz, and others. Not only mathematicians and philosophers but doctors and engineers studied and taught Newtonian curricula by the end of the eighteenth century. Thus Newtonianism, with its several meanings, permeated the emerging professional and popular cultures of the Enlightenment.

JESSICA RISKIN

Alfred Nobel (1833–1896), Swedish chemist, engineer, and philanthropist

NOBEL PRIZE. By his will of 1895, Alfred Nobel, inventor of dynamite and smokeless powder, left his estate to a nonexistent corporation, soon established as the Nobel Foundation. He directed that the net income from his endowment be given in equal shares for discoveries or inventions in physics, chemistry, and physiology/medicine made during the previous year that had contributed most to the welfare of mankind; and also for literature of an idealist tendency and for contributions to world peace. The prize in economics in the name of Alfred Nobel was established by the Bank of Sweden in 1968. The Royal Swedish Academy of Sciences awards the prizes in physics, chemistry, and economics, and the Karolinska Institute the prize in physiology/medicine.

The requirement that the prizes be given for current work was not observed in the first awards, made in 1901, and rarely thereafter. Since prizes can be given for old work newly recognized as significant for recent innovations, the lag can be considerable, almost fifty years in the case of one of the physics laureates of 2000. Early winners, like Wilhelm Conrad Röntgen for X rays (physics, 1901), Guglielmo Marconi and Ferdinand Braun for wireless telegraphy (physics, 1909), Adolf von Baeyer for contributions to chemical industry (chemistry, 1905), Emil von Behring for serum therapy (physiology/medicine, 1901), Ronald Ross for the etiology of malaria (physiology/medicine, 1902), and many more in physiology/medicine, were the sorts of awardees Nobel had in mind. But the requirement of applicability dissolved along with that of currency. Many of the science prizes, particularly in physics, have gone to academics for discoveries whose applications, if any, were not foreseen at the time of the award.

The distribution of awards has often been scrutinized for signs of bias and indications of national rankings. Some have noticed biases toward Germany, experimental discoveries, and exact measurement in the prizes given during the first two or three decades. But the leading theorists usually were honored if they lived long enough and the early favoritism of

Germans, owing to the closeness of the German and Swedish scientific communities, did not undermine confidence in the merit of the decisions. Since World War II, Americans have dominated the science prizes. The first crop of winners, in 1901, were two Germans and a Dutchman working in Germany. The prizes of 1926 (to proceed in 25-year intervals) went to two Germans, an Austrian working in Germany, a Frenchman, a Swede, and a Dane. This increase in awardees does not indicate the arrival of team research but the operation of a rule that played an important part in Nobel politics: a prize committee can hold over a prize for a year, after which it must either be awarded or pocketed by the academy for the research of those who failed to find a winner. The accounting of 1926 includes two prizes postponed in 1925.

Twenty-five years later we reach a new world. The science prizes of 1951 went to two Americans, a South African working in the United States, an Englishman, and an Irishman. (The quantity of winners reflected not belated prizes but small-team collaboration in accelerator physics.) In 1976, Americans made a clean sweep, five of them sharing the three prizes available.

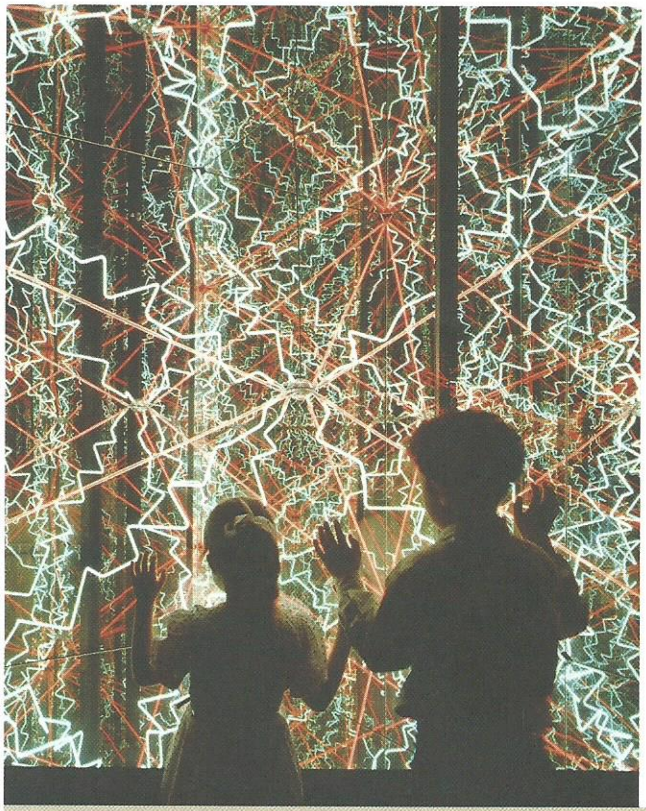
Of greater interest to many winners than the competition among nations is the monetary value of their awards. Although it has varied, it has ended the century as it began, at about six times a top professorial salary. One of Nobel's purposes in making the prizes so valuable was to draw attention to the importance of science and technology. The size of the prize, inflated by the participation of the Swedish royal family in the gala award ceremony and dinner, helped make its message. Science needs no such advertisement today. Nobel had in mind the lone investigator, such as himself, working out ideas that strike only the prepared mind of an individual genius. By insisting that no more than three people can share one science prize, the Nobel Foundation has institutionalized its founder's romantic notion of scientific creativity. In our age of team research, when experiments can involve hundreds of people, Nobel's notion of a single informing creative impulse no longer catches the circumstances of science.

In this predicament, the Nobel Foundation might become more companionable, and permit the award of science prizes to groups as it does the peace prize. Failing that, it might consider enlarging the scope of science to include its history. Most historians still work alone.

J. L. Heilbron

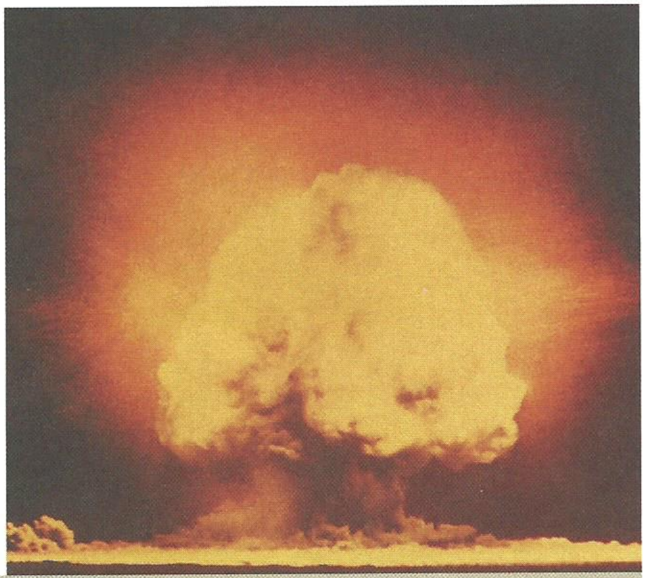
NOBLE GASES. The least reactive of the chemical elements proved the most fruitful guide to their interrelations. Some twenty-five years after Dmitrii Mendeleev first worked out his periodic table, Lord Rayleigh (John William Strutt), formerly James Clerk Maxwell's successor as Cavendish professor of physics at Cambridge, discovered that the nitrogen he drew from the air had a specific weight greater than that of the nitrogen derived from mineral sources. He asked publicly for ways to resolve the discrepancy and then hit on the solution himself. He read a paper, then a century old, in which Henry Cavendish mentioned an unoxydizable residue of gas he obtained after sparking atmospheric nitrogen with oxygen.

While Rayleigh tried to collect enough of this residue to weigh it, William Ramsay, a leading British chemist alerted to the problem by Rayleigh's request, isolated the residue by more effective chemical means. It weighed enough to account for the discrepancy of one part in two hundred that had started Rayleigh's quest. By 1895, they could announce the discovery of a constituent of the atmosphere they named "argon" (from the Greek for "lazy") because it declined chemical intercourse. Ramsay then looked for other trace gases by examining air and argon liquefied by then-new cryogenic techniques. Neon ("novel"), krypton ("hidden"), and xenon ("strange") quickly put in an appearance in the spectroscope and then the balance. So did helium, already named and known as the suppositious source of certain otherwise unattributable lines in the solar spectrum.


A display of neon lights enhanced by mirrors

The sluggishness and aloofness of the noble gases put them in a class apart. Astonishingly, Mendeleev's chart could accommodate the five newcomers, confirming its importance and renewing its mystery. The only pinch came with argon, whose atomic weight placed it after potassium, but whose nobility placed it before. It took almost twenty years and the invention of the concept of isotope to resolve this problem of precedence. In 1919, Francis Aston at the Cavendish made the first crisp separation of isotopes using neon gas in a mass spectroscope he had invented. Meanwhile the reversal at argon-potassium (and at cobalt-nickel and iodine-tellurium) helped to alert chemists and physicists that something other than atomic weight regulated the properties of the elements.

The discovery of the noble gases was almost a prerequisite to unraveling the complexities of radioactivity. Ernest Rutherford and Frederick Soddy identified the "emanation" from thorium as a new and flighty member of the noble family, now called radon; the occurrence of a decaying nonreactive gas in their experiments provided the clue for working out their theory of the transmutation of atoms. Radium also gives off a radioactive emanation and the two similar (indeed chemically identical) noble gases offered an early example of isotopy. However, the lightest of the noble gases proved the weightiest. Helium is often found with uranium and other active ores. With the spectroscopist Thomas



The explosion at the Trinity test of the first plutonium bomb, performed at Alamogordo, New Mexico, on July 16, 1945.

Royds and an apparatus made by the virtuoso glass blower Otto Baumbach, Rutherford demonstrated in 1908 that the alpha particles emitted from radioactive substances turned into helium atoms when they lost their electric charge. In 1910–1911 he showed that alpha particles acted as point charges when fired at metal atoms, and devised the nuclear model of the atom to explain the results of the scattering and to deduce that helium atoms have exactly two electrons. The replacement of atomic weight by atomic number (the charge on the nucleus) as the ordering principle of the periodic table followed. Rayleigh, Ramsay, Aston, and Rutherford all received Noble Prizes in large measure owing to their work on noble gases.

J. L. Heilbron

Nuclear physicist Igor Vasilivich Kurchatov (1903–1960), leader of the Soviet atomic bomb project

NUCLEAR BOMB. After the discovery of radioactivity and the relativistic equivalence of matter and energy, scientists realized that vast amounts of energy must be stored within the atom. Most insisted, however, that the enormous potential of atomic energy for industry and also for war could never be exploited in practice. More power would have to be fed into an atomic device than could be extracted; the threat of atomic weapons was consigned to science fiction. Increasing knowledge of the atomic nucleus did not affect this assumption. Once James Chadwick in 1932 had demonstrated the existence of neutrons, Leo Szilard inferred that a nucleus would not repel a neutron as it would a positive particle and might release more neutrons than it captured, leading to a chain reaction. But he was unable to pursue his ideas further.

Meanwhile astrophysicists suggested as early as the 1920s that the energy of stars came from the fusion of hydrogen atoms to form helium. Hans Albrecht Bethe and George Gamow worked out a convincing mechanism for the process in agreement with observation in 1937–1938. Their theory was of purely cosmological interest, since nobody imagined that humans could attain the temperatures required to set the process off. But then came the surprise discovery of fission at the end of 1938 by Otto Hahn and Fritz Strassmann, as interpreted by Lise Meitner and Otto Robert Frisch. Within a month it was widely understood that nuclear fission could release energy far in excess of any chemical combustion or explosion. To achieve the necessary chain reaction required obtaining a critical mass of potentially fissile material (that is, a large enough sample that the neutrons can participate in the chain before being lost to the environment).

Szilard persuaded Albert Einstein to inform President Franklin Delano Roosevelt about the possibility of a nuclear bomb. Roosevelt set up a scientific committee under the National Bureau of Standards to look into it. Meanwhile, atomic scientists were investigating the question in Germany, France, and Britain. Niels Bohr and John Wheeler had in 1939 proposed a mechanism for fission from which it followed that uranium 235 (U-235), although only about 0.7 percent of natural uranium, would be more suitable than the common isotope U-238. In March 1940 Frisch, now in England, and another refugee, Rudolf Peierls, completed their memorandum, "On the Properties of a Radioactive Super-Bomb," which showed that the critical mass required for fission on a large scale was much less than had been presumed. The British government set up the MAUD committee to investigate; they reported in the summer of 1941 that a bomb would be feasible. They also suggested methods to enrich the proportion of U-235 in uranium. In Germany Werner Heisenberg, as head of the Kaiser-Wilhelm Institut für Physik, set out the main tasks of a nuclear energy program. For about a year German research stayed ahead of the British, who at first thought to develop their own nuclear weapon but soon felt obliged to accept the absorption of their program into America's.

Anglo-American research disclosed that the newly discovered plutonium (created by bombarding U-238 with neutrons) would probably also be fissile. The American government, through the National Defense Research Council, began to pump money into the nuclear program even before

Pearl Harbor. In December 1941, what was to become the Manhattan Project began to take shape. In almost exactly a year Enrico Fermi and his team at Chicago achieved an atomic pile capable of a controlled chain reaction. Their accomplishment indicated that a plutonium bomb might be no more difficult to make than a uranium bomb. Huge factories in remote parts of the United States mushroomed into life—Oak Ridge in the Tennessee Valley (for separation of U-235) and Hanford in Washington state (for production of plutonium).

A third major laboratory, established at Los Alamos, New Mexico, under J. Robert Oppenheimer, assembled many outstanding nuclear scientists, including Bohr, Bethe, and Edward Teller, to design the bombs. They decided that uranium could be detonated by firing (with ordinary explosives) two subcritical masses together, but the plutonium would fizzle if made critical so slowly. Instead, a subcritical mass of plutonium would be made critical by suddenly increasing its density via an imploding charge outside it. War ended in Europe, and the failure of the German program was known, before the test in June 1945 of the plutonium bomb. The uranium bomb fell (without prior test) on Hiroshima and a plutonium bomb on Nagasaki in August. The shock of the invincible weapon forced the military leaders of Japan to capitulate.

The United States resumed testing in summer 1946. The Soviets, who had known about the Manhattan Project, resumed their own project, spurred on after August 1945 by fears that the Americans would use atom bombs to impose their supremacy over all. Helped by espionage (just how much is still debated), the Soviet Union exploded its own bomb in 1949. Shocked by this unwelcome surprise and revelations of past spying, the American government now pressed on to develop a thermonuclear device, the so-called H-bomb (for hydrogen bomb). Some scientists involved in the Manhattan Project, Teller for example, had even then wished to work on such a weapon, nicknamed the "super," since the fission bomb would create the temperatures and pressures to make fusion feasible. Both the United States and the Soviet Union developed hydrogen bombs and tested them in the early 1950s. Meanwhile the British, feeling they had been shut out of a program to which their scientists had originally contributed much, decided in 1947 to make their own nuclear armory. They have been followed by a number of other states.

Alex Keller

NUCLEAR MAGNETIC RESONANCE. The technique of nuclear magnetic resonance (NMR) emerged as a consequence of quantum mechanics. The orbital motions of electrons give atoms a magnetic dipole moment, which according to quantum theory can take only particular orientations in a magnetic field. One method to explore the effect involved sending a beam of atoms or molecules from a gas through a magnetic field and measuring the deflection. The so-called molecular-beam method could also measure the magnetic moment of an atomic nucleus, which resulted from quantum-mechanical spin. In 1937, I. I. Rabi, an expert in molecular beams, proposed applying an alternating magnetic field, oscillating at radio frequency, on top of the static magnetic field. The particles in the beam would suddenly switch orientation for particular frequencies of the alternating field, and the frequency depended on the magnetic moment—in particular, when the frequency of precession of the spin axis matched, or resonated with, the frequency of the applied magnetic field. Rabi and his group at Columbia University used the magnetic resonance technique to produce surprising results for the magnetic moment of the proton and the quadrupole moment of the deuteron by 1939.

World War II interrupted research on magnetic resonance, but also fostered the development of new radio frequency electronics that would aid future research. At the end of the war physicists resumed work with resonance. One direction led to atomic clocks, which inverted the approach and used the minute difference between quantum-mechanical energy levels as the basis for a constant frequency. Another direction looked from the gases studied in the 1930s to solid matter. In 1946, a group under Felix Bloch at Stanford University and another under Edward Purcell at Harvard succeeded in detecting nuclear magnetic resonance in condensed matter. Bloch and Purcell shared the Nobel Prize in physics for 1952 for the work; Rabi had won in 1944 for the molecular-beam resonance technique.

Subsequent research brought NMR from the nuclear physics lab into diverse fields of science. In the early 1950s, Bloch's group found that the chemical environment of the nucleus—the close presence of nuclei of other chemical elements or molecules—affected the resonance frequency, as did couplings between the spins of nearby nuclei. The so-called chemical shift and spin-spin coupling suggested a powerful tool for chemistry. Organic chemists began using resonance signatures to tease out variations in molecular structure, and increasing use of NMR in the 1950s helped transform organic chemistry from painstaking test-tube analysis of chemical reactions to a quick mechanical process

Cross-sectional magnetic resonance image of the human head of structure elucidation. Solid-state physicists similarly took up NMR to reveal the internal structure of their samples.

The provision of standardized NMR devices spurred the spread of the technique to other fields. Varian Associates, a firm formed in 1948 near Stanford, led the market. Varian's founders had long experience with microwave electronics and close associations with Stanford physicists and engineers. These ties extended to Bloch's group, and when Bloch and Stanford lagged in pursuing a patent on NMR the company convinced Bloch to file a patent and assign it the license. Varian would also hire several students of Bloch. Varian quickly capitalized when the chemical uses of the machine became apparent; it introduced the first commercial NMR spectrometer in 1952 for $26,000 and improved models in subsequent years. The role of Varian in NMR development demonstrates the indistinct boundary between industrial and academic research, and between basic and applied science.

Yet another use for NMR, perhaps the most widely known, appeared in medicine. In 1972, the chemist Paul Lauterbur proposed to use magnetic field gradients to distinguish NMR signatures from different portions of an object. The resulting scan could identify biochemical properties across a tissue sample, such as water content, blood flow, and cancerous growths. Groups in Aberdeen, Scotland, and Nottingham, England, soon scaled up NMR scanners for human use and commercial firms brought them to the medical marketplace. In the 1980s, the technique acquired its current name of magnetic resonance imaging, or MRI, which skirted public fear of things nuclear.

PETER J. WESTWICK

NUCLEAR PHYSICS AND NUCLEAR CHEMISTRY. Research into the atomic nucleus derived from the study of radioactivity, which flourished starting around 1900 as a program in both chemistry and physics; chemists sorted out the different radioactive elements and their decay products, and physicists elucidated the nature of the emitted rays. The physicist Ernest Rutherford, who would later deride most science outside physics as stamp-collecting, won a Nobel Prize in chemistry for his radioactivity research, but his work divided the physical from the chemical in the study of radioactivity. He posited the existence of the atomic nucleus in 1911. The subsequent atomic model of Niels Bohr, which combined Rutherford's nuclear atom with the emergent quantum theory, would establish the nucleus as the seat of radioactivity and encourage physicists to speculate about its contents. In 1919, Rutherford achieved the artificial disintegration of the nucleus by bombarding nitrogen atoms with alpha particles from radioactive substances. Hydrogen nuclei (protons) were knocked out of the nucleus by the impact of the alphas.

Most nuclear models through the 1920s built nuclei out of protons and electrons, since their opposite electric charges would prevent electrical repulsion; also, the apparent expulsion of electrons from the nucleus in beta decay argued for their inclusion. Application of the new quantum mechanics to the nucleus later in the decade, especially by George Gamow, provided a model of a liquid drop held together by surface tension, which nuclear particles could escape through quantum tunneling. But the presence of both protons and electrons defied attempts at detailed descriptions, and the nucleus seemed to reveal deficiencies in quantum mechanics. Bohr believed, characteristically, that the problem required bold steps and suggested that conservation of energy and momentum failed at the nuclear level. Wolfgang Pauli instead proposed a new nuclear particle, later dubbed the neutrino, to save the energy balance in beta decay.

Another new particle solved the problem and reconciled nuclear models with quantum theory. In 1920, Rutherford suggested that protons and electrons could combine to form a neutral particle, a "neutron," which might reside in the nucleus. The hypothetical neutron attracted little attention, but James Chadwick, a protégé of Rutherford's at the Cavendish Laboratory in Cambridge, looked for it through the 1920s. In 1932, Chadwick found it in radiation, studied by Frederic Joliot and Irène Joliot-Curie, emitted by beryllium when it was exposed to alpha rays. Physicists soon accepted the neutron as a single elementary particle, and new models of the nucleus, notably one proposed by Werner Heisenberg, gradually accommodated the neutron alongside protons and removed electrons from nuclei. The neutrino and neutron, along with the positron (detected, like the neutrino, in 1932), were followed in the 1930s by other new particles, such as the cosmic-ray mesons. The floodgates opened to the proliferation of so-called elementary particles that emerged from the heads and machines of physicists in ensuing decades.

The neutron provided a useful projectile with which to probe the nucleus, since its neutral charge experienced no electrical repulsion. Physicists at the time were developing devices to accelerate charged particles to energies high enough to penetrate the electrical barrier of the nucleus. In another corner of the Cavendish, John D. Cockroft and Ernest T. S. Walton had built a high-voltage apparatus, which they used in 1932 to fire a proton into a lithium nucleus and disintegrate it into two alpha particles. Simultaneously, Ernest Lawrence in Berkeley was developing a circular particle accelerator as an easier route to high energies. Then in 1934, Joliot and Joliot-Curie bombarded aluminum with alpha particles from a polonium source and found that they created an isotope of phosphorous, which decayed radioactively. The process provided a way to produce radioactive isotopes in the lab. A group under Enrico Fermi in Rome quickly extended the results in a systematic bombardment of elements with neutrons; when they got up to uranium, their results suggested that neutron capture produced new transuranic elements.

The artificial production of radioisotopes, whether using rays from natural radioactivity or accelerated particles, required chemistry to disentangle the decay processes and identify short-lived parent species and their daughter isotopes by comparison to elements with similar chemical behavior. Nuclear research labs of the 1930s restored the sort of collaboration between physicists and chemists that had marked radioactivity research thirty years earlier. Lawrence, who recruited a group of chemists to his cyclotron program, noted the indistinct boundary between the existing disciplines and wondered whether to call the field nuclear physics or nuclear chemistry. An international community emerged among the major centers in nuclear science: the Cavendish under Rutherford; Lawrence's group in Berkeley; Joliot and Joliot-Curie in Paris; Fermi's group in Rome; Bohr's institute in Copenhagen; a group under Igor Vasilyevich Kurchatov in Leningrad; and the Riken laboratory in Tokyo under Yoshio Nishina.

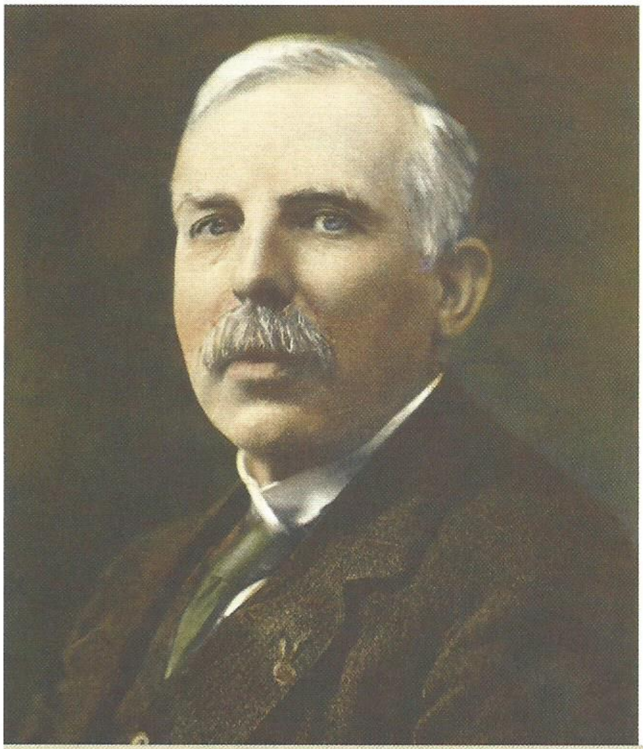
A momentous collaboration formed in Otto Hahn's chemistry institute in Berlin, where the physicist Lise Meitner worked with chemists Hahn and Fritz Strassmann. The Berlin group began studying the decay modes of the postulated transuranics produced by neutron bombardment of uranium; after several years of analysis, Hahn and Strassmann convinced themselves that the suppositious transuranics behaved chemically like elements much further down the periodic table. The chemical evidence implied that uranium could split into two lighter elements in a nuclear version of cell fission, but the conclusion challenged the results of Fermi's group and seemed to contradict the nuclear theory developed by physicists. As chemists, Hahn and Strassman hesitated to take such a bold step. They appealed to the physicist Meitner, in exile from the Nazis, who with her nephew and fellow physicist Otto Robert Frisch showed how to reconcile fission with nuclear physics.

Physicists and chemists alike recognized the importance of nuclear fission after its announcement in January 1939, and both disciplines would play central roles in the military and industrial application of nuclear energy in World War II and afterwards. The discovery required the sort of interdisciplinary collaboration possible in Hahn's institute, which helps explain why physicists alone failed to notice the effect earlier. Fission exemplifies the interplay of chemistry and physics within a common field of nuclear science; Rutherford's early Nobel Prize symbolized the difficulties Nobel committees experienced in distinguishing physics from chemistry in the nuclear science of the 1930s.

The contributions of nuclear scientists to the war ensured public prestige and government funding for their postwar programs, which attracted new practitioners and allowed the construction of more and larger particle accelerators. The devices encouraged the separation of a new field of high-energy physics from nuclear physics, but also supported thriving research. Nuclear physicists recognized the existence of several different mesons and incorporated the various types into the theory of nuclear forces. Based on evidence of the stability of certain isotopes, Maria Goeppert Mayer postulated an alternative nuclear structure based on shells of nucleons instead of the liquid drop; theorists later reconciled the competing models in a rotational scheme combining single-particle states with surface oscillations. Nuclear chemists, especially a group under Glenn Seaborg, meanwhile were using cyclotrons, nuclear reactors, and even nuclear bombs to produce new transuranic elements up to and beyond element 100 in the period table. Both nuclear physics and nuclear chemistry earned state support by continuing as prime contributors to the military and industrial development of nuclear energy in the cold war.

PETER J. WESTWICK

NUCLEAR POWER. The dream of obtaining cheap and useful power from the atomic nucleus originated with the discovery in 1896 that energy emanated from radioactive atoms. By the beginning of the 1920s, Einstein's theory of the equivalence of mass and energy and Ernest Rutherford's experiments in nuclear disintegration together indicated that energy is contained in every atomic mass. Popularizers of the day declared that the energy in just one glass of water could power a giant ship across the Atlantic. But leading physicists at the time agreed with Rutherford in dismissing the prospect of nuclear power as "moonshine." However, nuclear power suddenly became a realistic possibility when Otto Hahn and his collaborators in Berlin in 1938 discovered that uranium is capable of fission upon bombardment with neutrons. Physicists soon learned that in the process of fission, a large quantity of energy is released along with more neutrons, possibly enough to make a chain reaction. While an uncontrolled chain reaction would make a nuclear explosion, a controlled one in a nuclear reactor would provide a source of energy that could be transformed into electrical power.


Ernest Ruterford (1871–1937), inventor of the nuclear model of the atom

In Chicago at the end of 1942, as part of the Manhattan Project to build the atomic bomb, a team led by Enrico Fermi achieved a controlled chain reaction with an experimental nuclear reactor. The project soon established a reactor research station near Chicago at the site of what would become the Argonne National Laboratory. In 1946, the United States Congress established the Atomic Energy Commission (AEC), a civilian agency with sole control of all nuclear research. At Argonne, which in 1948 became the AEC's center for the development of reactors to produce electrical power, investigators pursued the main elements of reactor design: types of fissionable core, moderators to slow and absorb neutrons, and coolants.

In the late 1940s, as the Cold War set in, the AEC concentrated on nuclear weapons and gave nuclear power a relatively small budget. Admiral Hyman Rickover grew impatient. Rickover, a career navy officer and visionary engineer, was bent on developing nuclear-powered ships. Obtaining authority in 1947 to build a reactor for the navy, he persuaded Congress in 1949 to commit the AEC to the project. At Rickover's urging, the agency contracted with the Westinghouse corporation for a reactor suitable to power a submarine. A prototype version achieved full-power operation in 1953, and the next year a modified version of the reactor was successfully installed in the submarine *Nautilus.*

In 1954, the Republican Congress revised the Atomic Energy Act to permit private ownership of nuclear reactors and the leasing of nuclear materials to industry. The chairman of the AEC told the public that nuclear power would bring "energy too cheap to meter." Both the AEC and partisans of atomic energy in the Congress also spoke of an "atomic power race" with the Russians to bring nuclear power to the Third World. Under AEC sponsorship, Westinghouse constructed a scaled-up version of the *Nautilus* reactor for electrical power generation at Shippingport, Pennsylvania. It went on line in 1957, generating 60 megawatts of power. That year, making conditions for private nuclear power more favorable, Congress limited industry's liability for nuclear accidents and provided hazard insurance at public expense.

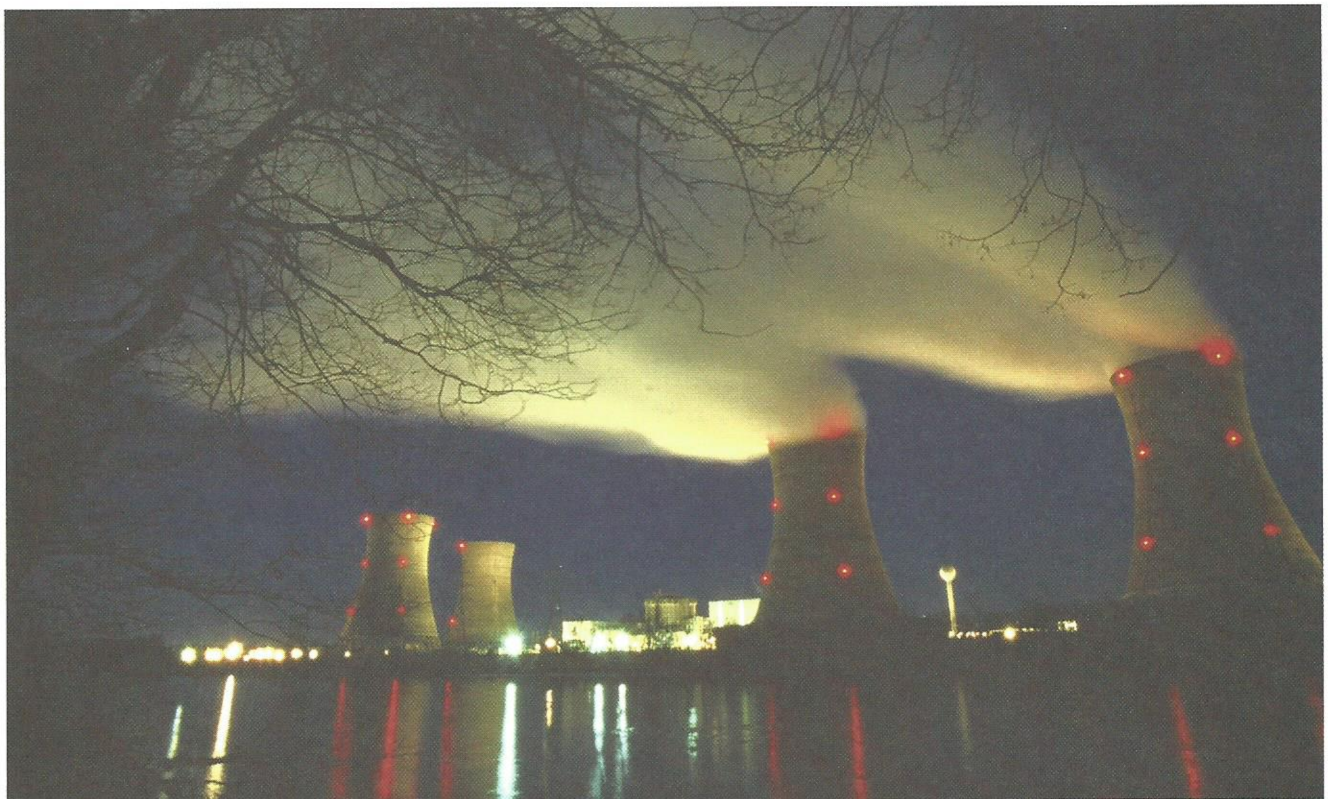
More than a dozen nuclear power plants were operating in the United States by 1967. By 1975, in the wake of the Arab oil embargo and the resulting energy shortage, about 225 plants were on order, under construction, or in operation. And by the late 1970s, nuclear power plants generated 13 percent of the nation's electricity. Nuclear power was also under rapid development in France and Japan. Neither had adequate resources of coal or natural gas to fuel its power needs, and the oil embargo prompted both to intensify their commitment to reactor generation of electricity.

Meanwhile, in the United States, environmentalists had been taking aim at the rapidly developing nuclear power industry and its patron, the AEC. Critics raised questions about the disposal of the burgeoning radioactive wastes; about the safety of reactors themselves, particularly the emergency core-cooling systems designed to prevent overheating and meltdown; and about the effect of the heated water that reactors disgorged into rivers, lakes, and streams on aquatic life. In 1970, as the result of a suit brought by environmental groups, the AEC was compelled to take into account all potential environmental hazards in the licensing of nuclear plants. To many observers, the AEC seemed to have a conflict of interest because it was responsible for both the promotion and the regulation of nuclear power. In 1973, Congress broke up the AEC, awarding the agency's promotional and R&D functions to the newly created Energy Research and Development Administration (which in 1977 became the Department of Energy) and its regulatory functions to the new Nuclear Regulatory Commission.

The American nuclear power industry received a severe blow in March 1979 when operator errors at the nuclear power plant at Three Mile Island near Harrisburg, Pennsylvania, caused a failure in the cooling system, a partial meltdown of the nuclear fuel, and the expulsion of some 800,000 gallons of radioactive steam into the air above the surrounding Susquehanna Valley. Utilities canceled orders for more than thirty nuclear plants and no new orders were placed during the rest of the century. The accident at Chernobyl in 1986 further turned the public in the United States against nuclear power, and stimulated anxious questioning in Europe.

Since the 1950s, several nations have attempted to harness thermonuclear fusion for power generation. Since fusion burns hydrogen, which is abundant, fusion reactors would in principle be cheap to sustain and relatively environmentally clean. However, no nation has come close to making practical fusion reactors. Research focuses on magnetic confinement of fusion fuel, using, for example "Tokomaks," (an acronym from the Russian words for "toroidal magnetic chamber," the standard vessel used to contain the superheated hydrogen fuel) and inertial confinement fusion, which uses a fusion-fuel-containing pellet irradiated by X rays produced by high-energy lasers to symmetrically implode the pellet. Large laser facilities have been built to study ICF and the world's largest laser system, the stadium-sized 192-beam National Ignition Facility, is under construction in the United States. In the absence of a viable fusion reactor, nuclear power remains indispensable in the industrial economies of France and Japan, for example, where in the mid-1990s it provided 75 percent and 27 percent of their electricity, respectively. In recent years, the specter of global warming has revived interest in nuclear power in the West because nuclear plants do not produce greenhouse gases.

Daniel J. Kevles



Night view of the nuclear power plant on Three Mile Island near Harrisburg, Pennsylvania. The evaporation of water from the cooling towers kept the reactors at a safe temperature—except on March 28, 1979.